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Localization of Head-Mounted Vibrotactile Transducers

by Mary S. Binseel and Joel T. Kalb

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14. ABSTRACT
The Global Positioning System (GPS) and communications systems transmit information through visual and auditory channels, diverting attentional resources from other tasks and degrading situation awareness. The tactile channel is proposed as an alternative sensory modality in order to reduce visual and auditory load. Most systems currently used—use trunk- or extremity-mounted tactors. Consequently, little is known about the psychophysical parameters associated with head-mounted vibrotactile (VT) displays. This study investigated the ability of humans to determine the location of an activated VT transducer (tactor). Seven tactors were placed on the head corresponding to electroencephalogram (EEG) locations for EEG recordings. The selected sites were F3, Cz, Pz, O2, T3, T4, and F8. Tactors were activated at vibration frequencies of 32, 45, and 63.5 Hz (1/2 octave center frequencies). The stimulus consisted of three cycles of 62.5 ms of tactor excitation followed by 187.5 ms of no signal. The stimulus level was about 10 dB above average tactor detection thresholds. Frequency and location were randomized, and 12 trials per frequency/location combination were presented. Participants responded by indicating at which of the seven locations they perceived the stimulus to be occurring. Results showed that participants correctly identified the activated tactor in 84% of the trials.

15. SUBJECT TERMS
tactor localization, tactile display, head-mounted tactile

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1. Objective

The purpose of this study was to determine human ability to identify by location ("to localize") which one of several head-mounted vibrotactile (VT) transducers ("tactors") had been activated.

2. Background and Motivation

The human sensory systems most frequently used in military displays (vision and audition) are sometimes overloaded. When Soldiers rely on visual or auditory displays, their situation awareness can be degraded due to the need to attend to the display. A proposed alternative sensory channel for Soldier displays is the tactile channel. The investigation and use of the tactile modality in Soldier applications is fairly recent, and the majority of investigations to date have been on trunk- or extremity-mounted tactors.

In military applications, VT displays are primarily being used to aid in orientation, navigation, and communication. The torso-mounted vest-like Tactile Situation Awareness System (TSAS) has been shown in numerous studies to improve orientation and navigational tasks in a multitude of applications from Navy frogmen to astronauts (Castle and Dobbins, 2006; Chiasson et al., 2002; Griffin et al., 2001; McGrath et al., 2004; McTrusty and Walters, 1997; Nordwall, 2000; Rochlis and Newman, 2000; Ryan, 2000; Schrope, 2001). The TSAS is effective but not necessarily compatible with dismounted Soldier equipment, such as ballistic vests. Also, Soldiers do not need the complexity of TSAS, because they operate in a more two-dimensional realm than pilots or frogmen for tasks such as navigation. Tactile belts are a more common design for these tasks, and have been shown to improve dismounted navigational accuracy and have good performance in military operational environments (Elliott et al., 2006; Krausman and White, 2006, 2008; Redden et al., 2006).

Tactile displays can also be used to impart more abstract information such as in command-and-control applications. Merlo et al. (2006) reported a study in which four commands were transmitted to a small unit of Soldiers via hand signals or a VT display. Results showed faster detection of and response to signals when they were transmitted via the VT display. Soldiers commented that they preferred the VT display because it allowed them to use their vision to maintain their situational awareness without the need to frequently check their leader for hand signals.

By presenting information to more than one sensory channel, performance can be improved over using any single channel in isolation. Akamastu et al. (1995) used a finger-mounted tactile display to provide feedback to subjects locating and selecting targets on a computer screen. The use of tactile feedback in the task produced a quicker motor response than other feedback systems.

The tactile displays discussed thus far were primarily used for torso, arm, or hand applications. However, these are often not good locations for dismounted Soldier operations, due to equipment incompatibility and thermal considerations. Additionally, Ho and Spence (2007) found that when the head is not aligned with the body, the perception of the location of a tactile signal is impaired when the signal is presented on the torso. These factors make the head a potentially better choice for tactile displays aiding in navigation or providing directional information about the environment (e.g., sniper detection). Tactors can be mounted on the head with a dedicated harness or it might be feasible (if acceptable to the appropriate system proponent) to integrate them into headgear already worn, such as helmets or caps.

Although the head may be a beneficial location for tactors, the viability of mounting tactors on the head has not been fully explored. Questions regarding basic perceptual issues, such as sensitivity, acuity, localization, etc., in addition to user comfort and acceptability, need to be answered. Cassinelli et al. (2006) report on a pilot study of an “artificially extended skin” concept they call “haptic radar,” in which tactors were mounted on subjects’ heads to provide proximity warning for a ball swung towards their heads. The tactile input was significant in improving the wearer’s awareness of the object. In another study (Hawes and Kumagai, 2005) a tactile head mounted display (HMD) system was used for a navigation task. The results were that an eight-tactor HMD led to better performance than four-tactor displays mounted on either the chest or head. Soldier participants rated the head- and chest-mounted variants similar in many subjective areas such as ease of use. Additionally, Myles and Kalb (2010) reported that perception of VT signals on the head shows robustness in the presence of acoustic noise.

2.1 Head-mounted Tactor Perception Thresholds

Myles and Kalb (2009) investigated and obtained perception thresholds for tactors mounted at seven sites on the head. The sites used were from the set used for electroencephalogram (EEG) recordings. The selected sites were F3, Cz, Pz, O2, T3, T4, and F8 (see figure 1). Even-numbered sites are right-hemisphere sites and odd-numbered sites are left-hemisphere sites. Sites with a “z” are midline sites. In figure 1, the study’s right and left side sites are in green and the midline sites are in yellow (shown in both drawings). The sites were chosen so that all major non-facial skull bone regions (frontal, parietal, occipital, and temporal bones) were represented. A top view of the tactor locations is shown in figure 2.

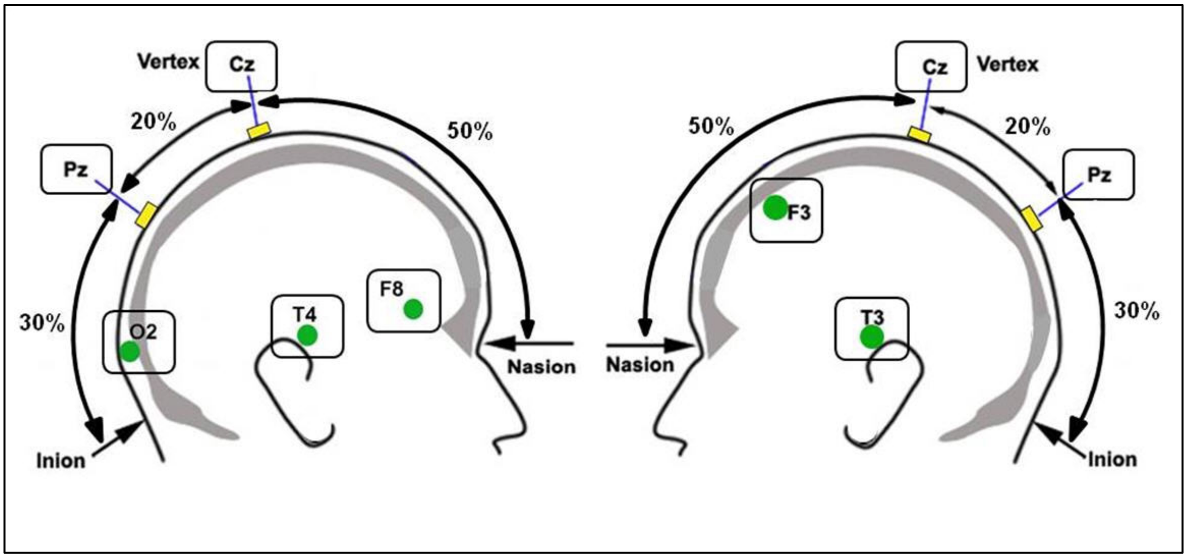

Figure 1. Tactor locations, side view.

Note: Figure 1 modified from:
http://www.medicine.mcgill.ca/physio/vlab/biomed_signals/images/10-20_sys.gif.

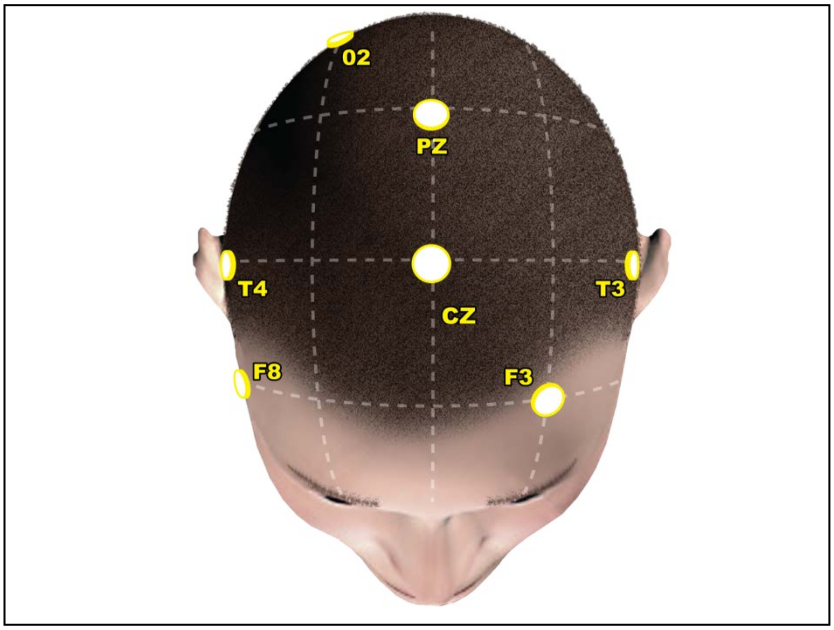

Figure 2. The seven tactor locations as viewed from above.

A pilot study determined that at frequencies above 64 Hz, a bone-conducted auditory signal was present in addition to the desired tactile signal. In order to isolate the tactile effects, thresholds were obtained for 32, 45, and 63 Hz, where these auditory signals were absent.

Results of the threshold measurements were that locations Pz, O2, and T3 had significantly lower thresholds than Cz, F3, and F8 (T4 was not significantly different than either group). Also, thresholds at 45 and 63 Hz were significantly higher than 32 Hz.

To build on this earlier study's results, the same seven tactor locations and three frequencies (with substitution of 63.5 Hz for 63 Hz for instrumentation reasons) were used in this localization study.

2.2 Tactor Localization Accuracy

Cholewiak et al. (2004) investigated the VT localization accuracy for the abdomen using 12, 8, and 6 equally spaced tactors arranged circumferentially. The tactors were separated by mean distances of 7.2, 10.7, and 14.0 cm, respectively. Localization accuracy increased as the number of tactors (and therefore location choices) decreased, with 74%, 92%, and 97% identification accuracy for 12, 8, and 6 tactors, respectively. They also found that the ability to localize improves when the stimuli are at or near body anchor points, such as joints, the spine, or the navel, (see also Cholewiak and Collins, 2003). Hawes and Kumagai (2005) placed tactors on the chest (8, circumferentially) and head (4 and 8, circumferentially). The Soldier task was navigation, not tactor localization, so no direct measure was obtained. However, for the head-mounted tactors, there was significantly better task performance using 8 tactors compared to 4, implying that participants were able to discriminate amongst the 8. Gilliland and Schlegel (1994) mounted 6, 8, 10, and 12 solenoid-type tactors on the head along an arc along the coronal median (from ear to ear), corresponding to inter-stimulus distances of 3.9, 2.5, 2.1, and 1.8 cm, respectively. Localization accuracy was 93%, 76%, 60%, and 47% for 6, 8, 10, and 12 tactors, respectively. Localization accuracy was significantly better for 6 tactors, as compared to 10 or 12 tactors and accuracy with 8 tactors was statistically better than for 12. Note that in all these studies increasing the number of tactors means decreasing inter-tactor distance. The number of tactors is therefore indicative of the proximity of the tactors to each other.

These results demonstrate the ability of humans to localize VT stimuli in general and tactors mounted on the head in particular; however, more basic research is needed in order to assess the potential of tactile HMDs. For example, the head-mounted tactors in the referenced studies were mounted in a single plane, and frequencies were not manipulated. The goal of this study was to determine human ability to discriminate the locations of the tactors placed at the same sites, and using all three frequencies, that were investigated by Myles and Kalb (2009) in their threshold determination study.

3. Methods and Procedures

3.1 Apparatus and Instrumentation

Seven C-2 tactors (figure 3) were used to generate the VT stimuli. With C-2 tactors, both vibration amplitude and frequency can be controlled. The tactors were calibrated by the methodology documented in Kalb et al. (2008). The C-2 tactor is 1.2 inches in diameter, 0.31-inches thick and weighs 17 grams. A piston of 0.3 inches in the center of the tactor housing moves perpendicularly to the plane of the tactor housing to create the VT signal.

Figure 3. The EAI C-2 tactor.

Note: Figure 3 from: http://www.eaiinfo.com/Tactor Products.htm.

The tactors were mounted in an experimental "halo" fixture (see figure 4). The halo was created using a size large Advanced Combat Helmet shell as a base. Holes were drilled through the helmet at the seven locations (refer to figure 1), allowing spring-loaded, screw-in tactor positioners to be mounted at each location. Sections of the helmet were removed in order to allow visual inspection of the tactor/head contact and to lighten the assembly. Tactors were epoxied onto ball-jointed plates at the end of the positioning rods. The piston in the tactors moves above and below the surface of the tactor housing during activation, so a rigid fiber washer was placed between the back of the tactor and the plate so that the piston would not impact the plate during use. There were five additional posts emplaced through the helmet shell to act as a rudimentary positioning and suspension system. The entire halo assembly was counterweighted via a weight suspended with a cord through an overhead pulley so that less than 1 oz of weight was applied to the head. This was done so that the weight of the helmet did not cause greater contact pressure for the top tactors. This was also for comfort reasons; a normal helmet has a suspension system of bands or pads to spread the weight of the helmet over the surface area of the enclosed head, but with the halo, the weight would be borne by the contact areas under the top three positioning posts. This was found to cause a comfort problem during instrumentation development. The contact pressure of each tactor was adjusted and equalized for each participant as detailed in the procedures section.

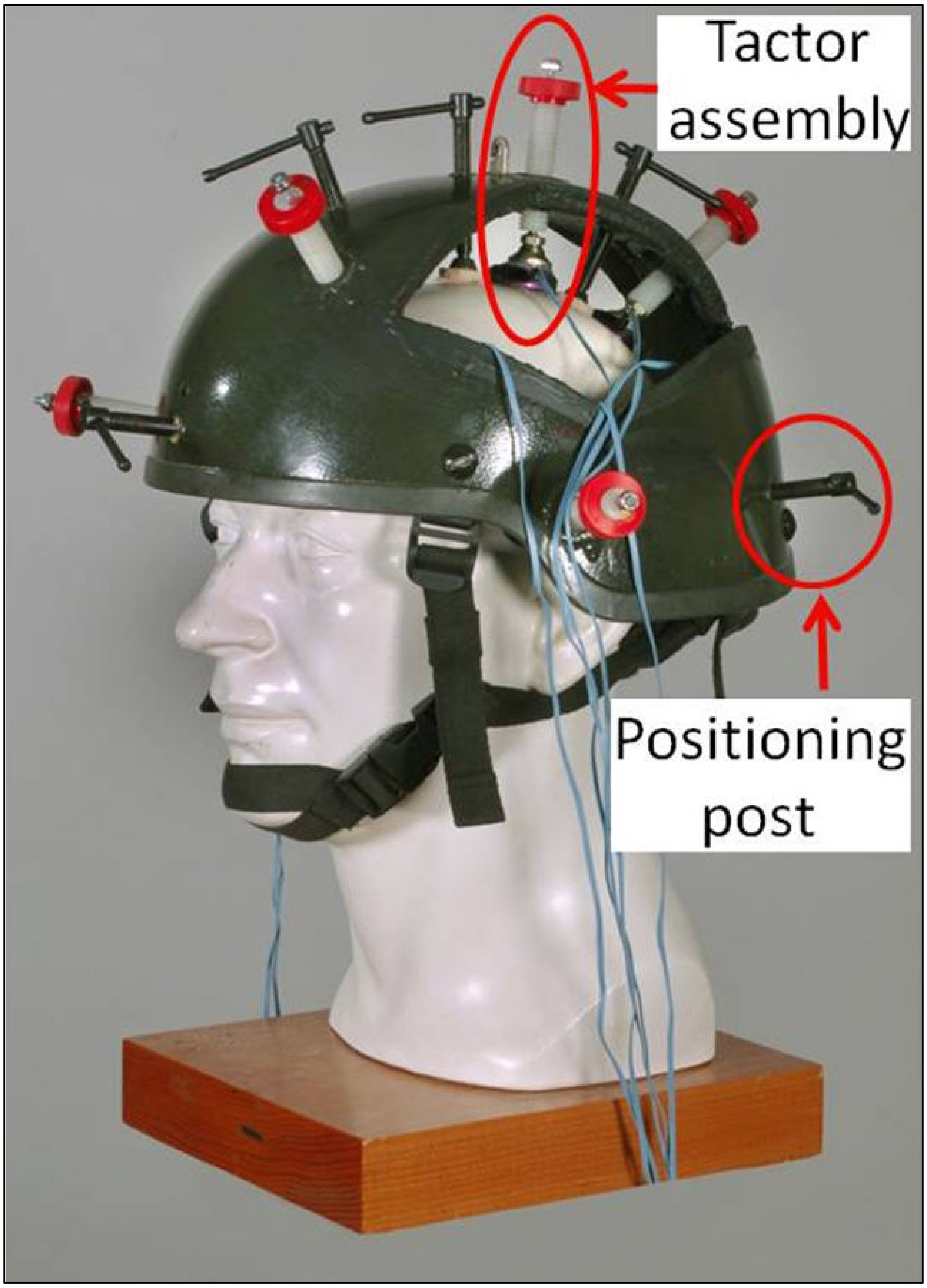

Figure 4. "Halo" experimental fixture.

The response methodology entailed the subject touching a mannequin head at the analogous location they perceived the origin of the tactile signal on their head. The mannequin was marked with duct tape at the seven tactor locations and positioned in front of the participant. Manual data collection was used to record the location indicated by the subject. Figure 5 shows the complete experimental setup with the halo fixture on the head of the subject, and the mannequin used for response.

Figure 5. The experimental setup.

3.2 Stimuli

The tactor stimulation was designed to present a rapid “tap-tap-tap” sensation to the subject; the “taps” were presented at one of the experimental frequencies (32, 45, and 63.5 Hz). Each trial stimulus consisted of three 62.5-ms cycles of tactor excitation at that trial’s frequency with an interval of 187.5 ms between excitations, for a total cycle time of 250 ms (25% duty cycle), a stimulus time of 750 ms (3 cycles), and 562.5 ms from onset of the first tactor excitation to the completion of the third. Each tactor excitation was contained in a pulse envelope comprised of rise, sustain, and fall phases. Rise and fall phases followed a half cosine response while the sustain phase was at full amplitude modulation. Figure 6 (a), (b), and (c) illustrate the stimuli for the 32-, 45-, and 63.5-Hz stimuli, respectively. Figure 6 (c) shows the various phases of the tactor excitation stimulus cycle.

Tactor activation was controlled by computer. The sinusoids were generated by Tucker-Davis Technology (TDT) equipment, which produces sinusoids with amplitudes of 10 V. These in turn were attenuated 13 dB to reduce the amplitude from the 10 V TDT output to 2.25 V to drive the tactors. At the sustain phase of all the cycles, the amplitude was near the maximum signal achievable with the C-2 tactors and was well above average tactor detection thresholds for all locations (Myles and Kalb, 2009) to ensure that the stimuli were easily perceived.

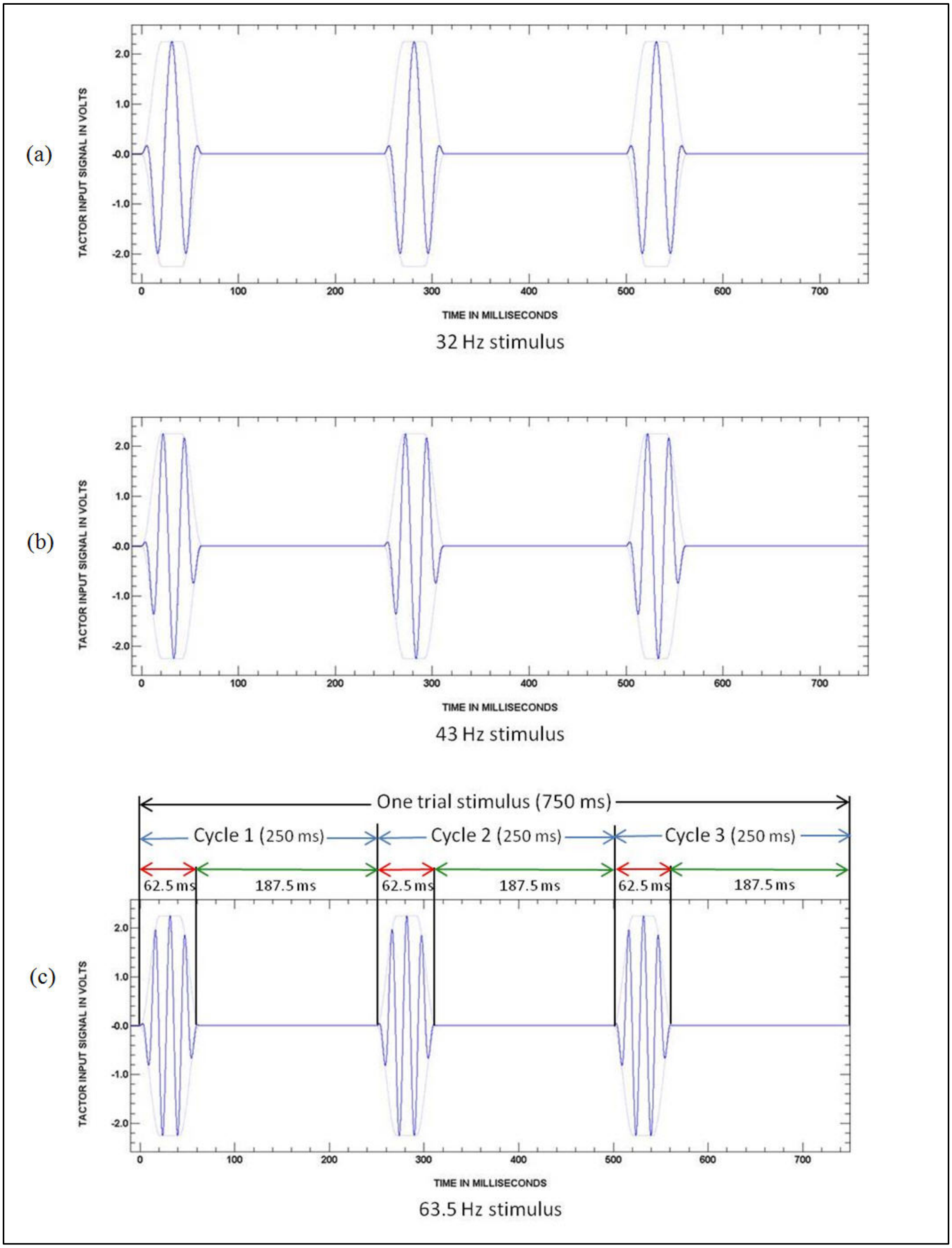

Figure 6. Graphical representation of the vibrotactile stimuli for (a) 32 Hz; (b) 43 Hz; and (c) 63.5 Hz. The phases of the stimuli are shown in (c).

3.3 Experimental Design

There were two independent variables in the study: tactor location (seven: F3, Cz, Pz, O2, T3, T4, and F8), and tactor excitation frequency (three: 32 Hz, 43 Hz, and 63.5 Hz). The dependent variable was the percent of correct location identifications. The study was a full-factorial within-subject repeated-measures design. Five repetitions of each combination of the seven tactor locations and three frequencies were administered, for a total of 105 trials. Trials were random, controlled by the computer that generated the stimuli presentations. All 105 trials were randomized from one list; there was no blocking by frequency or location, nor was there a requirement to complete a complete set of all combinations before repeating.

3.4 Participants

Ten Marines participated in the study. Due to the preponderance of males in the volunteer pool, seven of the participants were male and one was female. Ages ranged from 18–25 years, with a median age of 20.7 years and a mean age of 21.5 years (SD=2.8 years). All had head sizes that could be accommodated with the tactor halo. The investigators have adhered to the policies for protection of human subjects as prescribed in Army Regulation 70-25 (AR 70-25).

3.5 Procedures

A Volunteer Agreement Affidavit explaining the study procedures and any risks was administered to all volunteers. The participant was then familiarized with the experimental setup. The halo was fitted to the Marine's head, so that there was approximately the same standoff distance of the halo from the head over the entire enclosed area. Because the tactors were mounted normal to the surface of the helmet, tactor positioning was accurate for the selected sites; however, the absolute inter-tactor distance varied with head size. In this study, the primary objective was related to localization of tactile signals for various bone areas of the skull and not inter-tactor distance; therefore, the exact distances were not noted. The standoff supports were adjusted, and the nape band and chin strap adjusted for a snug helmet fit to prevent the halo from lifting as the tactors were advanced against the head. The tactors were then positioned to be in firm contact with the Marine's head. Tactors were tightened down until approximately the same pressure was being applied by each, as measured by visual inspection of the compression of the springs in the spring-loaded tactor positioning screws. The exact contact pressure of each tactor was not recorded, as the experimental setup did not allow for exact measurement of this force; however, all contact forces were approximately 1 Newton, based on the spring constant of the spring used in the halo. The tactors were then activated in sequence while the corresponding tactor position on the mannequin was shown to the subject. In order to remove perceived signal strength as a tactor identification aid, the subject was asked to note if there were any tactors that felt stronger or weaker than the others. Any noted tactors were adjusted by increasing or decreasing the contact pressure as appropriate and the process repeated until the subject reported equal sensation from all tactors, similar to the intensity-leveling process used by Gilliland and Schlegel (1994). This procedure allowed adjustment of the tactors and also trained the Marines in the experiment task. The Marines were instructed that if at any time during data collection that they perceived a change in a tactor's signal strength, they were to notify the experimenters. In the few cases when this occurred, the study was paused and the tactor adjusted.

After the adjustments were complete, data collection was initiated. The 105 trials were completed in approximately 15 min, for a total participant time of approximately 30 min. The halo was then removed and any participant questions answered.

4. Analysis and Discussion

In this study, there was an error made in instrumentation. When the test fixture was assembled, one of the tactors was mounted "upside-down," as compared to the others. The location of this tactor was Pz. The error was not noted until after six participants had been run, so the decision was made to leave it as is to complete the data collection. The piston in the tactor protrudes alternately from each side of the tactor housing during activation, so a signal was still being presented from the incorrectly mounted tactor. Also, the entire housing of the tactor vibrates (not just a point source of vibration from the piston), so the mis-mounting of the tactor might not adversely affect the data. At the start of each participant's data collection session, the investigators adjusted the contact pressure of each tactor until all tactors produced the same intensity perception. No subject reported that the Pz tactor felt "different" after adjustments were complete. Therefore, we do not believe that this incorrect mounting invalidated the data collected for this location; further, excluding this data does not change the results of the significance testing. We are including this location in this report, though caution is advised in extrapolating conclusions specific to this location.

4.1 Statistical Analysis

Prior to statistical analysis, the values for percent of correct identifications were transformed to rationalized arcsine units (rau) (Studebaker, 1985). This transformation is a nonlinear conversion, which compensates for the non-constant variance of scores resulting from a constrained range of possible scores—average percent-correct scores close to 0% or 100% will have smaller variance than those near 50% due to the compression of possible scores near the ends of the scale. The resulting data are normally distributed. Note that resulting rau values may be negative or exceed 100.

To ensure that responses were not due to random choice, a $\chi 2$ test was performed on the results of all tactor response for all frequencies. The null hypothesis that the responses were due to chance (only seven possible responses yields an expected value of 14% correct if tactors were randomly selected) was rejected for all cases at α=0.01.

When the data were analyzed using a repeated measures analysis of variance (ANOVA), there was a statistically significant difference of tactor location [F(6,54)=2.6187, p=0.027] and of tactor*frequency interaction [F(12,108)=1.8691, p=0.046]. There was no difference of frequency [F(2,180)=1.5464, p=0.24] at α=0.05.

Planned comparison of tactor location showed that localization performance was significantly worse for Cz than for both O2 [F(1,9)=8.7293, p=0.016] and T3 [F(1,9)=8.293, p=0.018]. No other significant differences were found at α=0.05.

Figures 7, 8, and 9 show the localization results in rau by tactor, frequency, and both tactor and frequency, respectively.

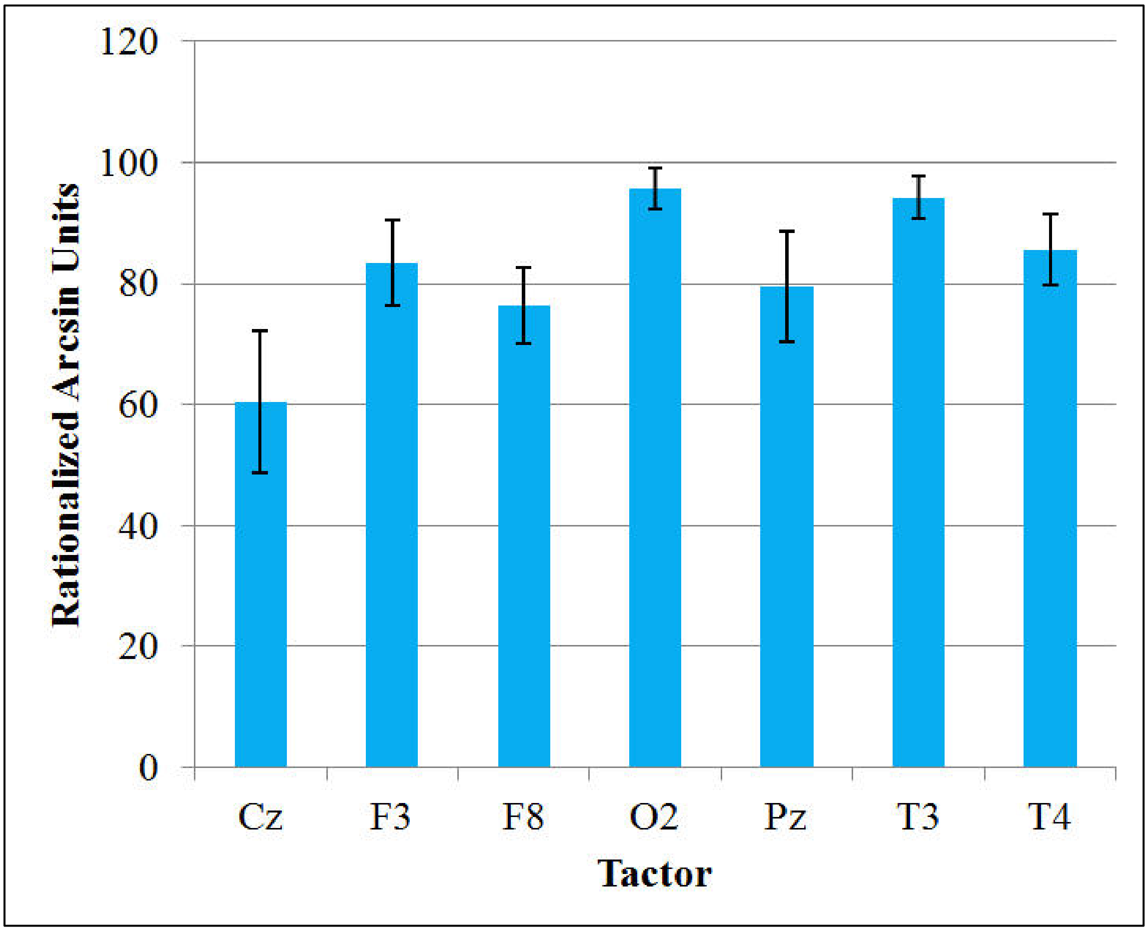

Figure 7. Localization performance in rau by tactor (with ±1 SE bars). There was main effect of tactor location (p=0.027).

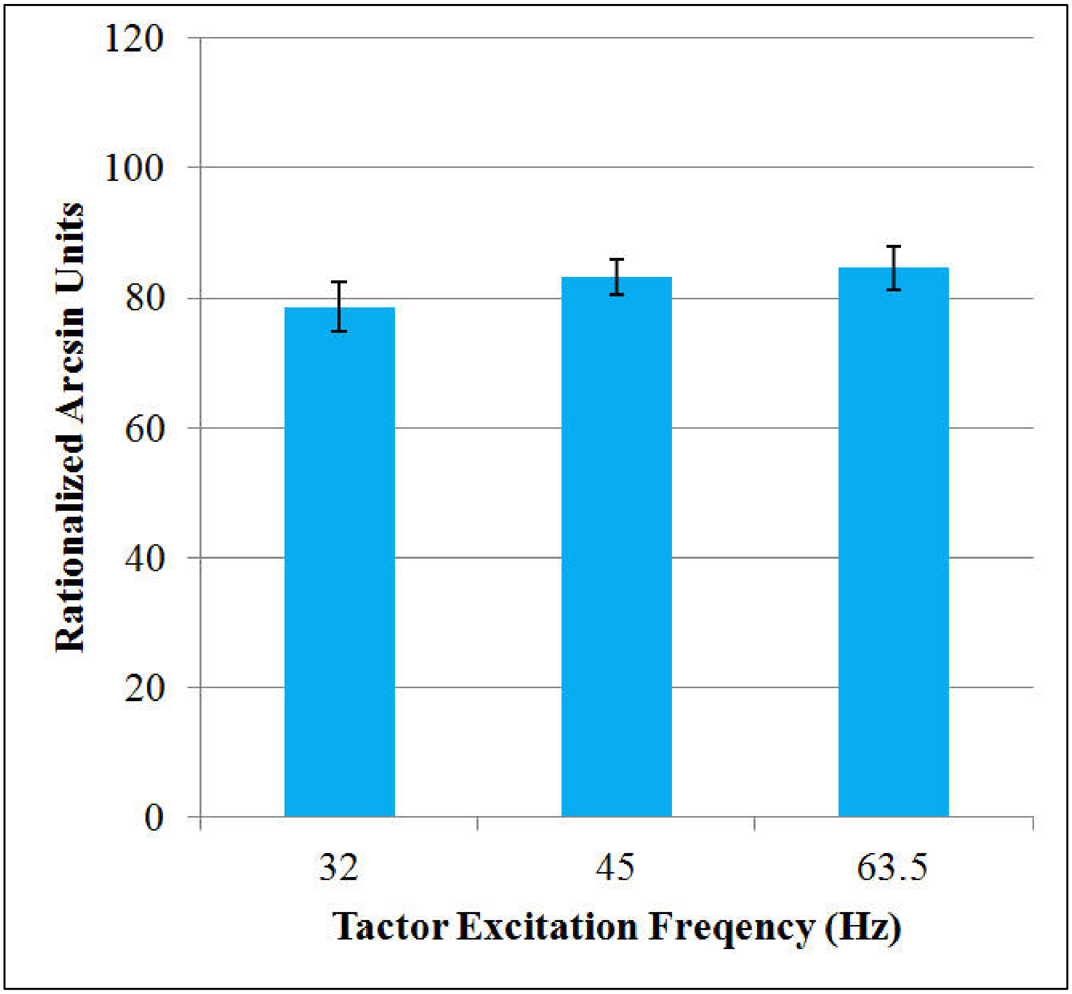

Figure 8. Localization performance in rau by frequency (with ±1 SE bars). Main effect for frequency was not significant ($p=0.24$).

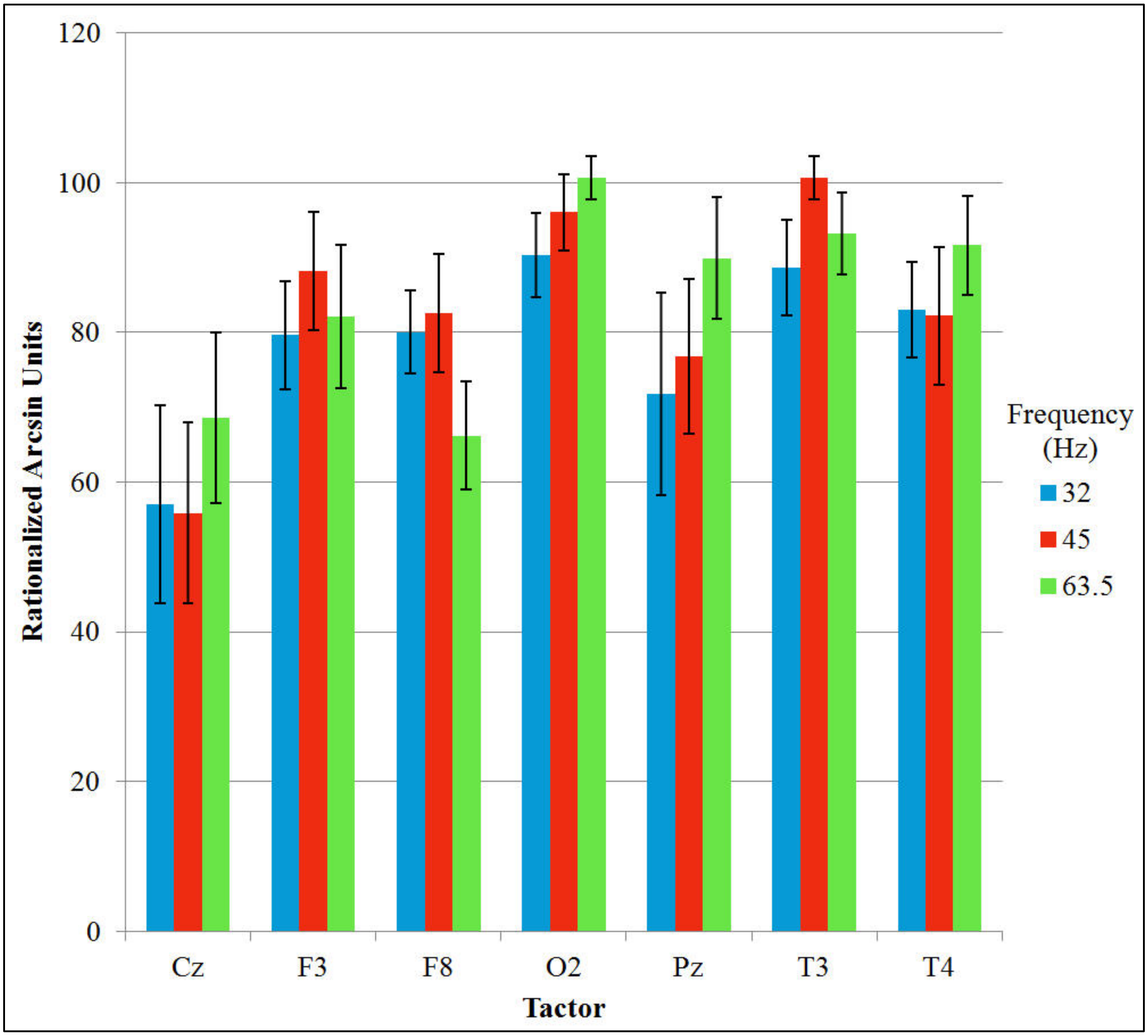

Figure 9. Localization performance in rau by both tactor and frequency (with ±1 SE bars). There was a significant interaction effect of location and frequency ($p=0.046$).

4.2 Confusion Matrices

Although there were no statistical differences in localization rates by tactor location, these matrices can provide insight into trends. The overall confusion matrix by tactor location is shown in table 1. Matrices for each individual are in the appendix of this report. Errors that contributed to ≤80% correct for any location are shown in red, bold font with thick cell borders. The most common errors were Pz↔Cz (presentation tactor-tactor identified); these tactors are the ones along the skull midline near the crown (Cz) and the top rear (Pz). The F3→Cz errors are from the tactor mounted at the top-front-left of the skull being identified as coming from near the crown; and the F8→T4 errors are the right-side-forward tactor being identified as the right-side-middle tactor site. Confusion matrices for each participant are in the appendix.

Table 1. Confusion matrix for all trials.

Σ		Response						
		Cz	**F3**	**F8**	**O2**	**Pz**	**T3**	**T4**
Stimulus Location	**Cz**	91	0	4	2	**51**	0	2
	F3	**30**	117	0	1	1	0	1
	F8	0	1	115	1	3	0	**30**
	O2	2	0	0	141	7	0	0
	Pz	**20**	1	0	6	120	2	1
	T3	2	4	1	0	3	139	1
	T4	2	0	14	3	0	0	131

4.3 Direction of Errors

Using an 80%-correct criterion when examining the confusion matrices, it can be seen that the majority of the errors involved the non-circumferential tactors (F3, Pz, and Cz) and the shift rearward of the right side tactors F8→T4. There were virtually no left↔right errors, defined here as T3↔T4 (presentation tactor-tactor identified) errors or T3↔F8 errors. Front/back errors, defined here as F3↔O2 or Pz↔O2, were also low. This latter result is especially promising for use of tactors in auditory cueing, as front↔back errors are not uncommon when localizing sound sources auditorally (see, for example, Wenzel et al., [1993] and Scharine [2005])

The largest contributors to incorrect identifications were Pz↔Cz errors, accounting for 71 of 196, or 36% of the errors. The next most common errors were F3→Cz, and F8→T4. Both of these reflect a shifting to the rear of the perceived stimulus from the actual stimulus location.

4.4 The Effect of Hair

One of the reasons for utilizing Marines as participants in this study was their typically very short hair length. However, one of the Marines who participated was female with hair that was too long to be left loose. In the grooming standards for female Marines (USMC, 2003) long hair must be worn up. Our participant wore her hair in a bun, and she controlled it with heavy use of hair gel. Although she unfastened the bun for the experiment trials, her hair was significantly stiffened due to the hair gel, yet her results fell within the range achieved by her male counterparts. Additionally, during equipment pilot testing, a few researchers of both genders and varying hair lengths wore the fixture and none indicated any difficulty in sensing the VT signals. This was a surprising result, as scalp contact was thought to be of importance in tactor identification. A possible explanation for this counterintuitive result is that the hair follicles themselves are aiding in tactor detection and identification as their hair strands are subjected to the stimuli. This result is anecdotal but encouraging.

5. Conclusions and Recommendations

The purpose of this study was to determine if humans can localize VT stimuli for seven non-coplanar locations on the head and three excitation frequencies. Prior studies have investigated tactors in a planar array (Hawes and Kumagai [2005]; Gilliland and Schlegel [1994]). The results of this study show that for the tactor location set and excitations frequencies used, tactor localization is possible.

The military application goal of this research is to determine the feasibility of using a head-mounted tactor display for imparting information to a Soldier. Exploitation of the underutilized tactile modality can shift information display from the often overloaded visual or auditory modalities. Therefore, a secondary objective of this study was to determine potential sites and frequencies for head-mounted tactors that would yield good localization results.

Results on thresholds reported in Myles and Kalb (2009) were that detection thresholds for sites O2, T3, and Pz were significantly lower than thresholds at Cz, F3, and F8. The T4 site was not significantly different than either of these two groups. These results were confirmed in Myles and Kalb (2010), which indicates that the lowest detection thresholds occur at O2, T3, T4, and Pz, which were significantly different than Cz, F3, and F8 over three noise conditions, including a quiet condition. The Pz site, found to have lower thresholds in the two Myles and Kalb studies, was not associated with better localization; however, in the present study the Pz tactor was the tactor that was mounted incorrectly.

Myles and Kalb (2009) report that the 32 Hz frequency resulted in significantly lower detection thresholds than either 45 or 63.5 Hz (which were not significantly different from each other), so the detectability of a stimulus at 32 Hz is higher than the other frequencies. Harris et al. (2004) conclude that for tactile stimuli, ". . . detection and localization are subserved by different sensory processes arranged in series. Specifically, we argue that the processes that underlie localization of a tactile stimulus are subsequent to, and dependent on, the process responsible for detection" (p. 3692). Therefore, 32 Hz is the best choice of the three frequencies for tactor excitation because it is better detected and has no contraindications for identification of stimulus location.

Based on the results of this study, and the prior threshold results, the circumferential sites of O2, T3, and T4 have promise for a head-mounted tactile display. The use of 32 Hz as a tactor excitation frequency would be preferred based on its lower detection threshold.

A display employing circumferential tactors would allow for information flow such as cueing the location of snipers or providing navigational instructions. The ability to determine active tactor location could also be used to impart abstract information by, for example, activating tactors in certain patterns or combinations.

Tactors can be mounted in a standalone cap or harness, or eventually in the lining of a combat helmet. Mounting a hard object such as the C-2 tactor inside a combat helmet is not acceptable due to the injuries that can be caused by such objects; therefore, hardware development would be needed to create, for example, a thin-film conformal tactor.

Further studies should investigate the effect of the number of tactors (and resulting differences in inter-tactor distance) in a circumferential array on tactor localization, the ability to localize additional tactors positioned non-circumferentially (for imparting elevation information, for example), the effect of signal duration and intensity on localization accuracy, the effect of tactor cuing on auditory and/or visual localization of sound sources, and the effect of hair and tactor mounting schemes, tactor identification reaction time, the effect of simultaneous activation of more than one tactor, effect of Soldier movement, and effect of horizontal position of the body on perception thresholds and tactor localization.

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Appendix. Localization Confusion Matrices

Table A-1. Confusion matrix for participant 1.

P 1		Response						
		F3	Cz	Pz	O2	T3	F8	T4
Stimulus Location	F3	9	5	0	1	0	0	0
	Cz	0	9	5	0	0	1	0
	Pz	0	1	12	0	2	0	0
	O2	0	2	1	12	0	0	0
	T3	1	1	0	0	13	0	0
	F8	1	0	0	0	0	12	2
	T4	0	1	0	0	0	0	14

Table A-2. Confusion matrix for participant 2.

P 2		Response						
		F3	Cz	Pz	O2	T3	F8	T4
Stimulus Location	F3	14	1	0	0	0	0	0
	Cz	0	6	9	0	0	0	0
	Pz	0	0	13	2	0	0	0
	O2	0	0	0	15	0	0	0
	T3	0	0	0	0	15	0	0
	F8	0	0	1	0	0	14	0
	T4	0	0	0	0	0	4	11

Table A-3. Confusion matrix for participant 3.

P 3		Response						
		F3	**Cz**	**Pz**	**O2**	**T3**	**F8**	**T4**
Stimulus Location	**F3**	8	7	0	0	0	0	0
	Cz	0	9	6	0	0	0	0
	Pz	0	1	14	0	0	0	0
	O2	0	0	0	15	0	0	0
	T3	0	0	0	0	15	0	0
	F8	0	0	0	0	0	13	2
	T4	0	0	0	0	0	0	15

Table A-4. Confusion matrix for participant 4.

P 4		Response						
		F3	**Cz**	**Pz**	**O2**	**T3**	**F8**	**T4**
Stimulus Location	**F3**	6	9	0	0	0	0	0
	Cz	0	4	11	0	0	0	0
	Pz	0	0	15	0	0	0	0
	O2	0	0	0	15	0	0	0
	T3	0	0	1	0	14	0	0
	F8	0	0	0	0	0	15	0
	T4	0	0	0	0	0	2	13

Table A-5. Confusion matrix for participant 5.

P 5		Response						
		F3	Cz	Pz	O2	T3	F8	T4
Stimulus Location	F3	9	6	0	0	0	0	0
	Cz	0	13	2	0	0	0	0
	Pz	0	0	14	1	0	0	0
	O2	0	0	0	15	0	0	0
	T3	0	0	0	0	15	0	0
	F8	0	0	0	0	0	12	3
	T4	0	0	0	1	0	0	14

Table A-6. Confusion matrix for participant 6.

P 6		Response						
		F3	Cz	Pz	O2	T3	F8	T4
Stimulus Location	F3	15	0	0	0	0	0	0
	Cz	0	15	0	0	0	0	0
	Pz	0	0	15	0	0	0	0
	O2	0	0	0	15	0	0	0
	T3	0	0	0	0	15	0	0
	F8	0	0	0	0	0	8	7
	T4	0	0	0	1	0	0	14

Table A-7. Confusion matrix for participant 7.

P 7		Response						
		F3	Cz	Pz	O2	T3	F8	T4
Stimulus Location	F3	15	0	0	0	0	0	0
	Cz	0	15	0	0	0	0	0
	Pz	0	5	10	0	0	0	0
	O2	0	0	0	15	0	0	0
	T3	0	0	0	0	15	0	0
	F8	0	0	0	0	0	9	6
	T4	0	0	0	0	0	0	15

Table A-8. Confusion matrix for participant 8.

P 8		Response						
		F3	Cz	Pz	O2	T3	F8	T4
Stimulus Location	F3	13	1	1	0	0	0	0
	Cz	0	15	0	0	0	0	0
	Pz	1	13	1	0	0	0	0
	O2	0	0	2	13	0	0	0
	T3	1	0	1	0	12	1	0
	F8	0	0	0	0	0	13	2
	T4	0	1	0	0	0	0	14

Table A-9. Confusion matrix for participant 9.

P 9		Response						
		F3	**Cz**	**Pz**	**O2**	**T3**	**F8**	**T4**
Stimulus Location	**F3**	13	1	0	0	0	0	1
	Cz	0	5	10	0	0	0	0
	Pz	0	0	15	0	0	0	0
	O2	0	0	3	12	0	0	0
	T3	2	0	1	0	12	0	0
	F8	0	0	1	1	0	13	0
	T4	0	0	0	1	0	8	6

Table A-10. Confusion matrix for participant 10.

P 10		Response						
		F3	**Cz**	**Pz**	**O2**	**T3**	**F8**	**T4**
Stimulus Location	**F3**	15	0	0	0	0	0	0
	Cz	0	0	8	2	0	3	2
	Pz	0	0	11	3	0	0	1
	O2	0	0	1	14	0	0	0
	T3	0	1	0	0	13	0	1
	F8	0	0	1	0	0	6	8
	T4	0	0	0	0	0	0	15

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List of Symbols, Abbreviations, and Acronyms

ANOVA	analysis of variance
EEG	electroencephalogram
GPS	Global Positioning System
HMD	head mounted display
rau	arcsine units
TDT	Tucker-Davis Technology
TSAS	Tactile Situation Awareness System
VT	vibrotactile

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